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Irfan Siddiqi

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14. ABSTRACT
We developed single-shot readout capability for superconducting qubits using dispersive measurements. The state of a quantum circuit is mapped unto the state of a resonant cavity which is then probed by microwave reflectometery. To maintain coherence, the cavity is weakly probed with only of order one microwave photon. Such a weak signal is detected by way of a superconducting parametric amplifier, developed with ARO support, which is nearly quantum limited in its noise performance. With this capability, we demonstrated several experimental milestones: high fidelity real time readout, active quantum feedback, and state tracking.

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Irfan Siddiqi
UU	UU	UU	UU		19b. TELEPHONE NUMBER 510-642-5620

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Report Title

Final Report: Integrated Josephson Parametric Amplifier Readout for Solid State Qubits

ABSTRACT

We developed single-shot readout capability for superconducting qubits using dispersive measurements. The state of a quantum circuit is mapped unto the state of a resonant cavity which is then probed by microwave reflectometery. To maintain coherence, the cavity is weakly probed with only of order one microwave photon. Such a weak signal is detected by way of a superconducting parametric amplifier, developed with ARO support, which is nearly quantum limited in its noise performance. With this capability, we demonstrated several experimental milestones: high fidelity real time readout, active quantum feedback, and state tracking.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/29/2012	1.00	M. Hatridge, R. Vijay, D. Slichter, John Clarke, I. Siddiqi. Dispersive magnetometry with a quantum limited SQUID parametric amplifier, Physical Review B, (04 2011): 0. doi: 10.1103/PhysRevB.83.134501
08/29/2012	2.00	R. Vijay, D. Slichter, I. Siddiqi. Observation of Quantum Jumps in a Superconducting Artificial Atom, Physical Review Letters, (03 2011): 0. doi: 10.1103/PhysRevLett.106.110502
09/16/2013	3.00	R. Vijay, C. Macklin, D. H. Slichter, S. J. Weber, K. W. Murch, R. Naik, A. N. Korotkov, I. Siddiqi. Stabilizing Rabi oscillations in a superconducting qubit using quantum feedback, Nature, (10 2012): 77. doi: 10.1038/nature11505
09/16/2013	4.00	K. W. Murch, S. J. Weber, K. M. Beck, E. Ginossar, I. Siddiqi. Reduction of the radiative decay of atomic coherence in squeezed vacuum, Nature, (07 2013): 62. doi: 10.1038/nature12264
09/16/2013	5.00	K. W. Murch, U. Vool, D. Zhou, S. J. Weber, S. M. Girvin, I. Siddiqi. Cavity-Assisted Quantum Bath Engineering, Physical Review Letters, (10 2012): 0. doi: 10.1103/PhysRevLett.109.183602
09/16/2013	6.00	K. W. Murch, E. Ginossar, S. J. Weber, R. Vijay, S. M. Girvin, I. Siddiqi. Quantum state sensitivity of an autoresonant superconducting circuit, Physical Review B, (12 2012): 0. doi: 10.1103/PhysRevB.86.220503
09/16/2013	7.00	I Siddiqi. Superconducting qubits: poised for computing?, Superconductor Science and Technology, (09 2011): 0. doi: 10.1088/0953-2048/24/9/091002
10/13/2014	9.00	S. J. Weber, S. Boutin, M. Boissonneault, J. M. Gambetta, A. Blais, I. Siddiqi, D. H. Slichter, R. Vijay. Measurement-Induced Qubit State Mixing in Circuit QED from Up-Converted Dephasing Noise, Physical Review Letters, (10 2012): 0. doi: 10.1103/PhysRevLett.109.153601
10/13/2014	8.00	R. Vijay, E. B. Weingarten, John Clarke, I. Siddiqi, J. E. Johnson, C. Macklin, D. H. Slichter. Heralded State Preparation in a Superconducting Qubit, Physical Review Letters, (8 2012): 0. doi: 10.1103/PhysRevLett.109.050506
10/13/2014	10.00	S. J. Weber, C. Macklin, I. Siddiqi, K. W. Murch. Observing single quantum trajectories of a superconducting quantum bit, Nature, (10 2013): 0. doi: 10.1038/nature12539

TOTAL: **10**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

“Dispersive Microwave Readout of Quantum Electronic Circuits”
International Microwave Symposium, Baltimore MD, 7/2011.

“Continuous Monitoring of a Superconducting Qubit”
Quantum Information Processing and Communication, ETH, Zurich, Switzerland, Septem-ber 6, 2011

“Continuous Monitoring of a Superconducting Qubit: From Quantum Jumps to Feed-back”
NASA QFT 1.0 Conference, Moeffett Field, CA, 1/20/2012.

“Continuous Monitoring of a Superconducting Qubit: From Quantum Jumps to Feed-back”
APS Meeting, Boston MA, 2/28/2012.

“Quantum Control of a Superconducting Qubit”
International Workshop on Quantum Noise and Measurement in Engineered Electronic Sys-tems, Dresden, Germany, 10/9/2012.

“Quantum Feedback in a Superconducting Qubit”
New Directions in the Quantum Control Landscape, KITP, Santa Barbara, CA 2/27/2013.

“Dissipation Enhanced Coherence in Superconducting Qubits”
11th US-Japan Joint Seminar, Nara, Japan, 4/12/2013.

“Weak Measurement & Squeezing Using the Lumped Element Josephson Parametric Amplifier”
CIFAR Cavities Meeting, Montreal, Canada, 5/3/2013.

“Weak Measurement & Squeezing Using the Lumped Element Josephson Parametric Amplifier”
Low Temperature Detectors 15, Pasadena, California, 6/25/2013

“Dissipation Enhanced Coherence in Superconducting Qubits”
Quantum Information Processing and Communication, Florence, Italy, 7/1/2013

“Taking Control of Superconducting Qubits”
International Superconducting Electronics Conference (PLENARY), Cambridge, MA, 7/8/2013

Measurement-induced entanglement between two spatially-separated superconducting qubits, M.E. Schwartz et al., Applied Superconductivity Conference (August 2014).

Enhanced dynamic range in N-SQUID lumped Josephson parametric amplifiers, A.Eddins et al., APS March Meeting (March 2014).

Quantum Zeno effect in a strongly measured superconducting qubit, D.H Slichter et al., APS March Meeting (March 2014).

Generating entanglement via measurement between two remote superconducting qubits, N. Roch et al., APS March Meeting (March 2014).

Continuous measurement of two spatially separated superconducting qubits: Quantum trajectories and feedback, M.E. Schwartz et al., APS March Meeting (March 2014).

Controlling dissipation in quantum circuits, K.W. Murch et al., PRAQSYS '13, Monterey CA (August 2013).

Suppression of the radiative decay of atomic coherence in squeezed vacuum, S. J. Weber et al., Quantum Information Processing and Communication International Conference, Florence, Italy (July 2013).

Suppression of the radiative decay of atomic coherence in squeezed vacuum, S. J. Weber et al., International Conference on Squeezed States and Uncertainty Relations, Nuremberg, Germany (June 2013).

Quantum feedback control in superconducting qubits: Towards creating and stabilizing entanglement in remote qubits, R. Vijay et al., APS March Meeting (Invited, March 2013).

Cavity assisted quantum bath engineering, K.W. Murch et al., APS March Meeting (Invited, March 2013).

Optimizing bandwidth and dynamic range of lumped Josephson parametric amplifiers, A.Eddins et al., APS March Meeting (March 2013).

Superconducting qubit parameter optimization for remote entanglement, N. Roch et al., APS March Meeting (March 2013).

Progress towards measurement-induced entanglement of remote superconducting qubits, M.E. Schwartz et al., APS March Meeting (March

2013).

Suppression of the radiative decay of atomic coherence in squeezed vacuum, S. J. Weber et al., American Physical Society March Meeting (March 2013).

Quantum control of a superconducting qubit with quantum bath engineering, K.W. Murch et al., Quantum Innovators Workshop, Waterloo, Canada (September 2012).

Superconducting qubit readout with parametric amplifiers: from quantum jumps to quantum feedback, D.H. Slichter et al., Quantum Innovators Workshop, Waterloo, Canada (September 2012).

Cavity aided quantum bath engineering with superconducting artificial atoms, K.W. Murch et al., Masterclass presentation, 62nd Lindau Nobel Laureate Meeting, Germany (July 2012).

Stabilizing Rabi oscillations in a superconducting qubit using quantum feedback, R. Vijay et al., APS March Meeting (March 2012).

Measurement-induced qubit state mixing from upconverted low-frequency noise, D.H. Slichter et al., APS March Meeting (March 2012).

Observation of quantum jumps in a superconducting quantum bit, R. Vijay et al., APS March Meeting (Invited, March 2011).

Quantum jumps and measurement backaction in a superconducting qubit, D.H. Slichter et al., APS March Meeting (March 2011).

Parametric amplification in a lumped element, low-Q Josephson resonator, R. Vijay et al., Applied Superconductivity Conference (Invited, August 2010).

Number of Presentations: 33.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Manuscripts:

Books

<u>Received</u> <u>Book</u>

TOTAL:

<u>Received</u> <u>Book Chapter</u>

TOTAL:

Patents Submitted

Josephson Junction Transmission Line Parametric Amplifier

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Andrew Eddins	1.00	
Chris Macklin	1.00	
Daniel Slichter	0.25	
Mollie Schwartz	0.25	
FTE Equivalent:	**2.50**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Nico Roch	1.00
Rajamani Vijayaraghavan	1.00
FTE Equivalent:	**2.00**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Irfan Siddiqi	0.13	
FTE Equivalent:	**0.13**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Daniel Slichter	
Total Number:	**1**

Names of other research staff

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

The Quantum Nanoelectronics Laboratory (PI: Siddiqi) at UC Berkeley was the first group to use superconducting parametric amplifiers (paramps) to readout the state of a superconducting qubit. This technology, developed under support from LPS/ARO, led to a number of milestones related to both high fidelity and efficient weak measurements of superconducting qubits outlined here. In particular, these paramps have enabled the first observation of individual qubit transitions or quantum jumps in real time (R. Vijay et al., PRL 2010), demonstrating the utility of such technology for high fidelity qubit measurement. These devices are robust and reliable, as LPS, IBM, BBN, and UC Santa Barbara have also successfully employed paramps supplied by the Berkeley group. In addition to these groups, since these first demonstrations of paramp-enhanced qubit measurement by the Berkeley group numerous other groups worldwide have employed similar paramps, albeit with different layouts of Josephson junctions and resonators, to achieve high fidelity readout—Yale, Delft, and NEC being notable examples.

Furthermore, the high measurement efficiencies achieved with superconducting paramps have facilitated a number of pioneering experiments in weak, continuous qubit measurement, where the rate at which qubit information is acquired is intentionally limited. These achievements include the implementation of measurement based feedback to stabilize Rabi oscillations (R. Vijay et al., Nature 2012) and the observation of quantum trajectories associated with the evolution of a qubit under measurement (K.W. Murch et al., Nature, July 2013). Taken together, these experiments constitute promising first steps toward the realization of continuous quantum error correction and efficient quantum state estimation utilizing weak measurements.

Finally, the Berkeley group has also successfully coupled squeezed vacuum produced by a paramp to a qubit to directly alter its decoherence properties (K.W. Murch et al., Nature, Oct. 2013), a task which has not been achieved in atomic physics. This experiment illustrates the potential use of superconducting paramps as sources of squeezed microwaves for applications in precision metrology and fundamental physics experiments exploring light matter interactions at microwave frequencies.

Technology Transfer

We distributed parametric amplifiers to other DOD scientists, and also helped other DOD funded teams design their own parametric amplifiers.